SURFACE ACOUSTIC WAVE STUDIES OF SURFACE CRACKS IN CERAMICS

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ABSTRACT

A 10 to 100 MHz surface acoustic wave (SAW) system with computer controlled data acquisition and analysis was used to study the detection and characterization of surface cracks in ceramics. Surface acoustic waves were generated by placing a focused transducer at a critical angle with respect to the test specimen. The scattering of surface waves into water by the surface cracks was detected, analysed in the time domain and correlated with the size and the shape of the cracks. At 100 MHz, the SAW technique can detect cracks as small as 25 μm deep on polished ceramics.

INTRODUCTION

Since surface flaws are the major source of failure in ceramics, the detection and measurement of these flaws are of considerable importance to the reliable application of high performance ceramics as structural components. High frequency surface acoustic waves (SAW) have the capability of detecting and characterizing surface flaws as small as 25 μm deep on smooth surfaces.

Surface waves are generated when an ultrasonic beam strikes the boundary of two media at a critical angle that is determined by

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the acoustic velocities of the media. The conventional technique for surface wave generation uses a wedge transducer in contact with the test specimen. However, the sensitivity of this contact method is limited to relatively large flaws due to coupling problems. One alternative is to use the immersion technique by detecting the leaky surface waves that are scattered from the flaw.

Derkacs et al[1] first used the immersion technique to generate 45 MHz surface waves on ceramics and found that the technique was quite sensitive to surface conditions such as grinding damage, as well as to defects. Later Khuri-Yakub et al[2] applied the technique to evaluate cracks simulating machining damage on silicon nitride rods. Predictions were made of the size of the cracks from their acoustic reflection coefficients. More recent work by Bond[3], successfully detected leaky waves from fatigue cracks in metals.

In our earlier work[4], the detection of surface flaws in ceramics was studied using the conventional surface acoustic waves generated by the contact technique as well as the leaky surface waves generated by the immersion technique. The comparison of the two methods clearly established the superiority of the leaky surface waves for the detection and measurement of surface flaws <100 μm.

The scattering theory developed by Kino[6] and Auld[7] provides the basis for the SAW measurement of surface cracks. The application of this theory to a penny-shaped crack of depth, a, predicts[8] that the acoustic reflection coefficient of the cracks, S_{11}, is proportional to a^3 when $\lambda \gg a$ and proportional to a when $\lambda \ll a$, λ being the SAW wavelength in the material. However, for the transition region, i.e. when $a \approx \lambda$, there is neither a satisfactory theory nor experimental data.

In the present study, the leaky surface waves have been used for the detection and measurement of surface flaws ranging in depth from 20 to 400 μm in silicon nitride using 10, 25, and 100 MHz frequencies (λ=560, 225 and 56 μm, respectively). This choice of frequencies and crack sizes has covered both the long wavelength and the short wavelength regimes as well as the transition region.

PRINCIPLE OF THE LEAKY SAW

An ultrasonic beam impinging at an angle other than normal onto the surface of a material immersed in liquid will undergo mode conversion as shown in Fig. 1(a). The intensity of the reflected and transmitted waves at various incident angles, can be calculated from the classical equations[5]. For silicon nitride immersed in water the analysis of the reflection and transmission coefficients indicates that depending on the incident angle, 28 to 37% of the incident beam will be reflected away at the surface and up to ~12%

will be converted to shear and longitudinal transmitted waves as shown in Fig. 1(b). The surface wave will also take a small portion of the intensity, reaching a maximum at the critical angle of shear waves. The critical angle is given by

$$\mathrm{Sin}\theta_c = \frac{V_l}{V_s}$$

where V_l is the acoustic velocity of liquid, and V_s is the shear wave velocity of the test medium. The surface waves generated by this method travel along the surface of the material creating reflections from surface flaws (Fig. 2). The reflected surface waves dissipate their energy back into the water which are received by the transducer. Thus, defects can be detected and their reflection coefficients measured. The leaky surface waves propagating at the water-specimen boundary attenuate rapidly hence only those flaws which are located very close to the point of incidence of the beam onto the specimen can be detected. This is in fact an advantage since reflections from the neighbouring flaws or shap edges do not affect the signal from the flaw of interest. Furthermore, this technique is practical and easy to perform since the water coupling yields more flexible and reproducible experimental conditions. This is important for testing small ceramic components where a high degree of accuracy and sensitivity is required.

EXPERIMENTAL PROCEDURE

Hot pressed silicon nitride (Norton's NC132) bars, 6x6x50 mm, were polished down to 1 μm surface finish. Artificial cracks were introduced on the polished surfaces by Knoop indentation. A Knoop indent can be approximated by a semicircular crack, its depth, a, being equal to the radius and its length being ∿2a. The surface length was measured under an optical microscope from which the depth was deduced.

A schematic diagram of the system used in this investigation is shown in Fig. 3. The system is capable of generating up to 100 MHz ultrasonic waves using a sharp pulse and a 100 MHz transducer*. The 100 MHz transducer employs a quartz buffer rod on which a piezoelectric lithium niobate crystal has been mounted on one side and a lens on the opposite side. For the lower frequencies, 10 and 25 MHz, Aerotech focused transducers were used. The detecting system uses a broad band power amplifier, a 100 MHz digital scope (HP1980) together with a digital waveform storage unit (HP19860). The latter enables averaging (up to 64 times) of the waveform and digitizing it to produce up to 501 points per waveform in main or

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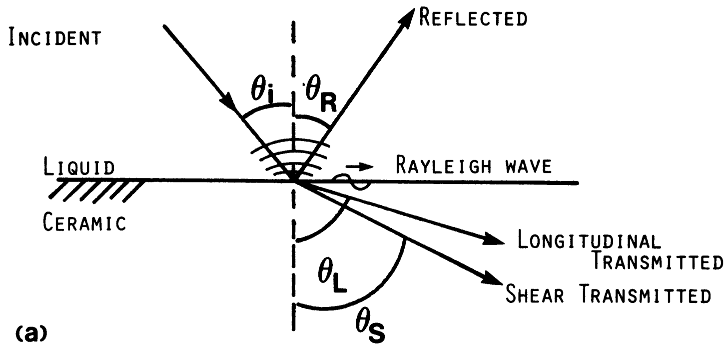
* Precision Acoustic Devices, Inc.



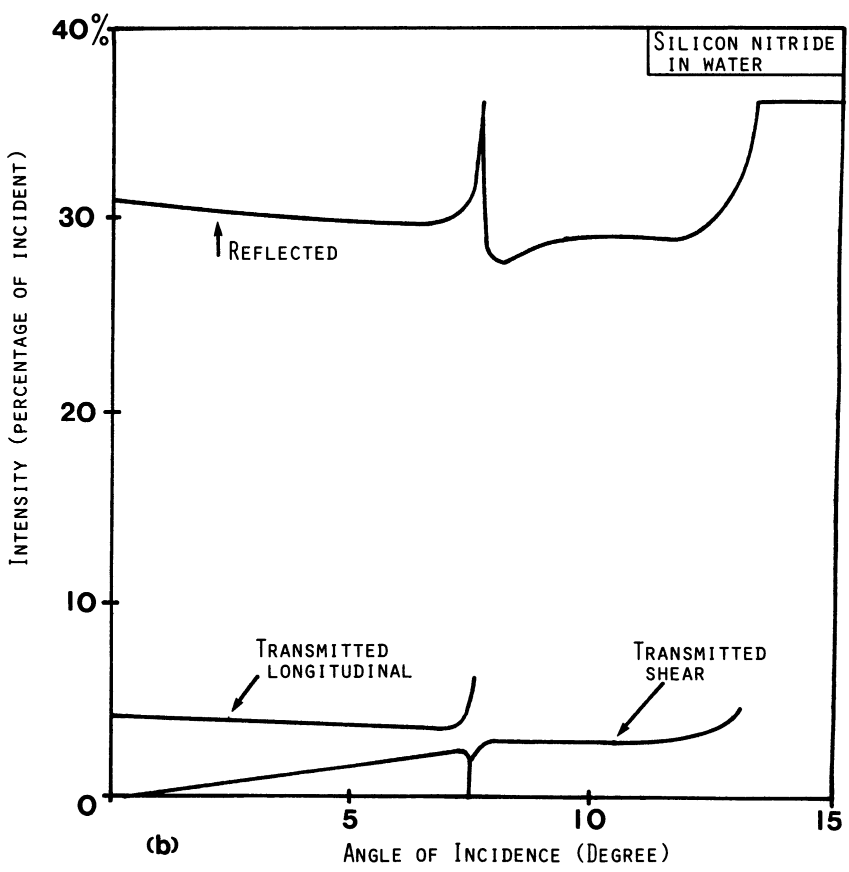


Fig. 1(a) Mode conversion at liquid-ceramic interface.

(b) Acoustic intensities of the reflected and transmitted waves at water-silicon nitride boundary as the function of the angle of incidence.

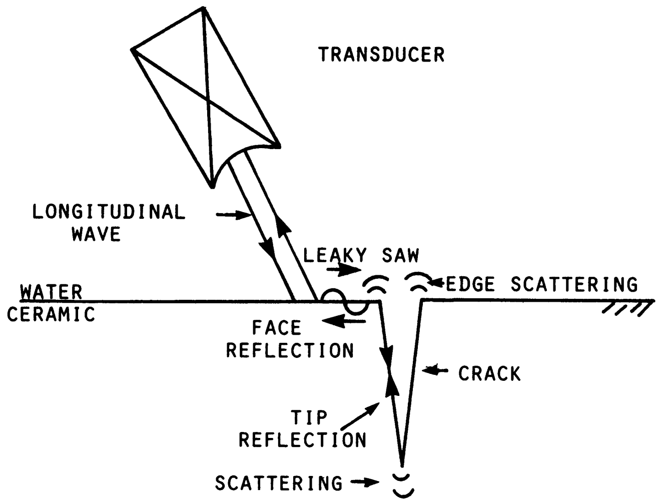


Fig. 2 The generation of leaky SAW and its interaction with a surface crack.

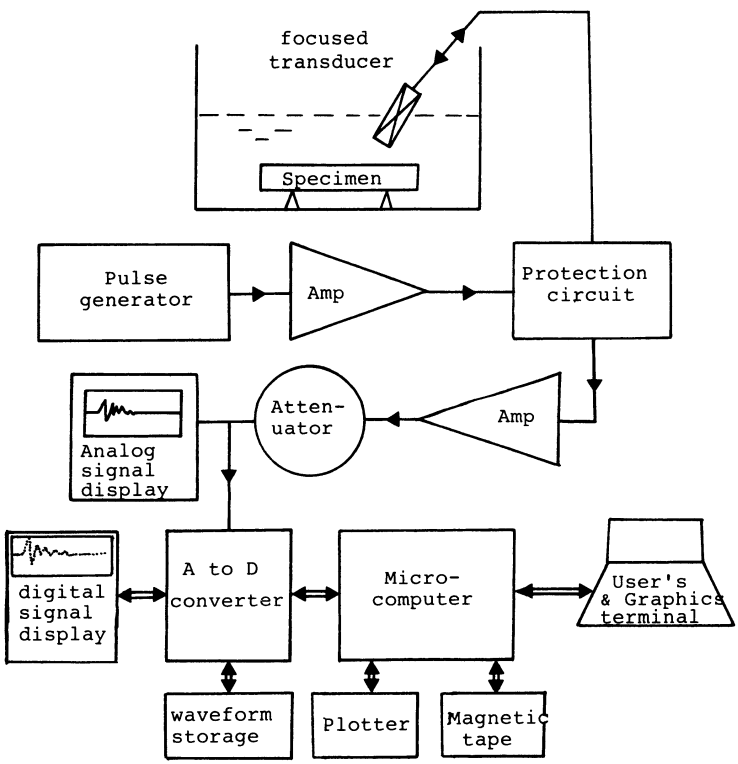


Fig. 3 A schematic of the SAW detection system and the computer analysis facilities.

delay modes. The delay mode was used to isolate the section of the waveform desired for analysis. The stored waveforms are transferred into a microcomputer (HP9845) for analysis in time and frequency domains.

For waveform analysis in the time domain, the total area under the waveform and the peak-to-peak amplitude normalized to the input signal amplitude were measured using;

$$S_{11} = \frac{A_2}{A_1}$$

where A_2 and A_1 are the crack signal and input signal amplitudes at the transducer. The results are presented in dB (20 Log S_{11}) and the normalized crack size,

$$Ka = \frac{2\pi}{\lambda} a$$

This work only presents the time domain data. Analysis in the frequency domain is currently underway and will be described in another publication.

RESULTS AND DISCUSSION

The acoustic reflections from various size (20-400 μm) Knoop indentation measured at 10, 25, and 100 MHz respectively, are shown in Figs. 4 to 6. The smallest crack detectable at 10 MHz was ∿100 μm, at 25 MHz around 60 μm and at 100 MHz was only 25 μm. This indicates that the sensitivity of the detection system increases with frequency, although the increase is not proportional due to the higher attenuation losses at high frequencies.

The two general regions predicted theoretically are quite clear from these figures. First, the rapid increase of the acoustic reflection with crack size in the long wavelength region where $\lambda > a$, followed by the slower increase and saturation corresponding to the short wavelength region where $\lambda < a$. The transition occurs when the crack size approaches λ. Furthermore, periodic maximas and minimas occur at certain crack sizes depending on the operating frequency.

This behaviour can be explained by analysing the interaction of surface waves with a Knoop indent demonstrated earlier in Fig. 2. First, there is the reflection of surface waves by the face of the crack which leaks into the water at an angle equal to θ_c and partly picked up by the transducer. Secondly, there is scattering by the edges of the crack mouth[9]. Finally, a portion of the incident Rayleigh wave continues along the surface of the crack and is subsequently reflected and/or diffracted by the tip of the crack. The interference between these reflections results in the varying behaviour of the flaw signal.

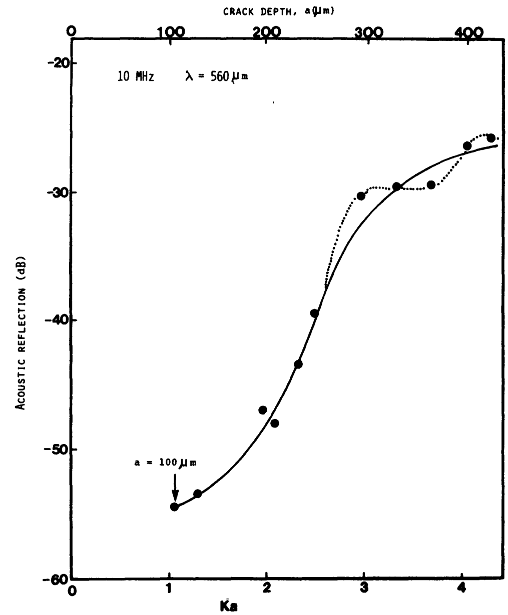


Fig. 4 The crack signal intensity as the function of the crack depth at 10 MHz.

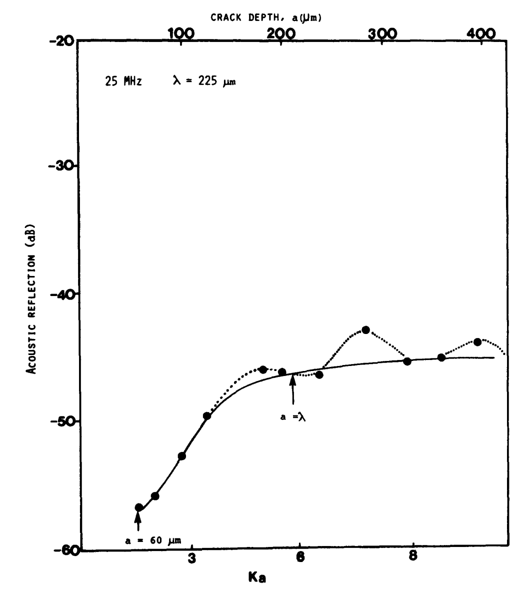


Fig. 5 The crack signal intensity as the function of the crack depth at 25 MHz.

The face reflection is dependent upon the crack face area, i.e. the depth and the length. For the depth effect, it is known[10] that the Rayleigh waves attenuate exponentially with depth so that at a depth of 1 to 1½ wavelength the particles of the medium under test are practically at rest. Thus it is reasonable to say that when the crack depth approaches the wavelength, the depth interaction with the SAW beam reaches its maximum. As for the length, the maximum interaction occurs when the crack length approaches the beam width, w, ($\sim$700 μm). Therefore, the reflection from the face of the crack increases with the crack size, or attains a peak value between λ and w.

On the other hand, the scattering by the crack mouth edges has very little effect on the overall crack signal intensity. Since these are spherical waves propagating in water in all directions only a small portion will reach the transducer. The tip reflections, however, may return along the same path as the face reflections to produce the second echo with a delay time determined by the size of the crack, and the Rayleigh wave velocity. The interaction of the two echoes may cause the resonance effect and periodic maxima and minima in the overall signal amplitude at certain crack sizes as shown by the dotted lines in Figs. 4 and 5. Maximas occur when $a=\frac{1}{4}(2n+1)\ \lambda$ which agrees well with the results of Dormarkas[11] obtained in the frequency domain. At 100 MHz, λ is too small and thus the resonance effect is not visible in the time domain.

If curves such as those in Figs. 4 to 6 are to be used for crack size estimation, they are valid only in the long wavelength regime. In the short wavelength region, however, due to the resonance and the amplitude saturation effects, the crack size estimation from the reflection coefficient will be extremely difficult. In this case, the measurement of the total area under the waveform is a better approach for crack size estimation since it increases proportionally with the crack size both in the long wavelength and the short wavelength regions at least for the crack sizes investigated in this study (Fig. 7).

CONCLUSIONS

Leaky surface waves are found to be very sensitive to surface defects and are capable of detecting and characterizing small surface flaws. Cracks as small as 25 μm can be detected on the surface of polished silicon nitride using 100 MHz leaky surface waves.

The acoustic reflection coefficient of cracks is dependent on the crack size, a, and the wavelength, λ. When $\lambda > a$ the acoustic reflection coefficient increases rapidly with the crack size. In this region the acoustic reflection of the crack can be used for crack size estimation. However, when a exceeds λ, saturation and

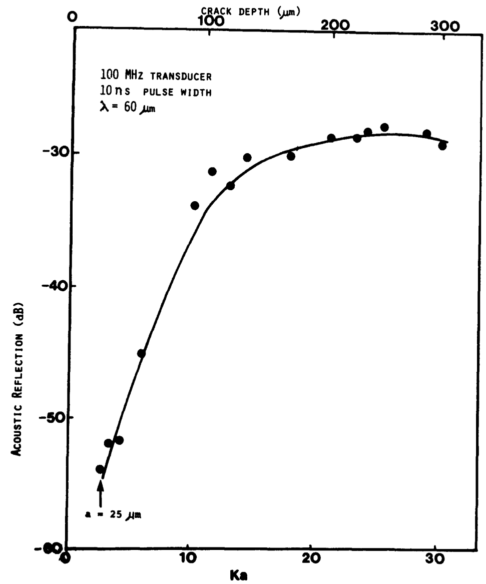


Fig. 6 The crack signal intensity as the function of the crack depth at 100 MHz.

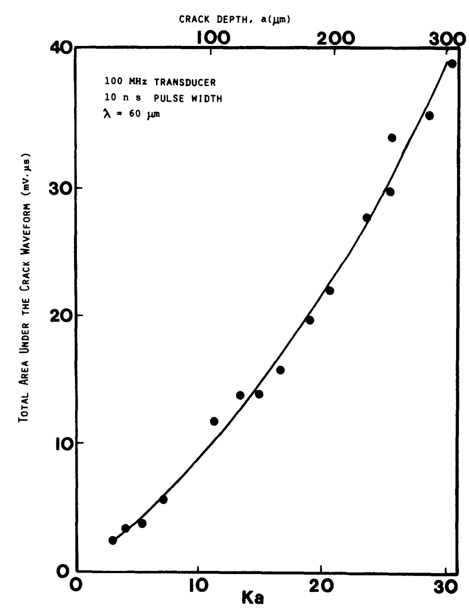


Fig. 7 The variation of the total area under the crack signal with the size of the crack at 100 MHz.

resonance effects were observed in the acoustic reflection coefficient, making the crack size estimation difficult. In this case, the measurement of the area under the waveform was found to be more appropriate for crack sizing.

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DISCUSSION

J. H. Rose (Ames Laboratory): I'd like to make a comment on the last three talks. For purposes of the characterization, it would be very valuable to have the complex scattering amplitude presented at least for one case as well as the impulse response.

For example, when you interpreted your data, you interpreted it in the time domain in terms of what went where and how this led to echoes, and I think it would be quite valuable to have those Fourier transforms.

A. Fahr: **Yes. In fact, that is part of the program. I didn't have the results to present here, but that is what we are going to do.**

J. R. Chamuel (Sonoquest): I'd like to say a few words about the reflections. The incident Rayleigh wave using the infinite down step which is the portion of the vertical side of the crack has to reflect and the other side goes around the corner. The portion that goes around the corner is tip to tip, most of that is converted into shear wave.

A. Fahr: Very little from that.